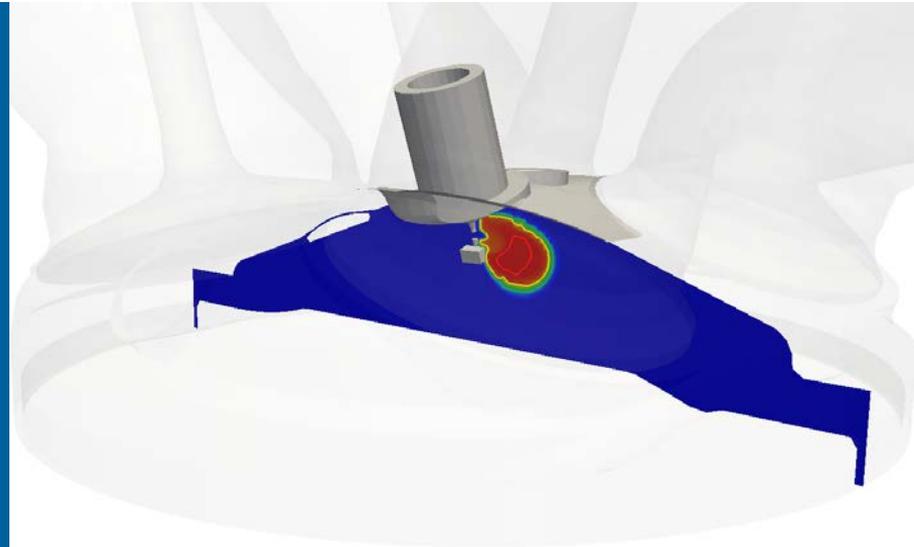


WE START WITH YES.

HIGH EFFICIENCY GDI ENGINE RESEARCH WITH EMPHASIS ON IGNITION SYSTEMS



PRINCIPAL INVESTIGATOR: THOMAS WALLNER

PRESENTER: RICCARDO SCARCELLI

TECHNICAL KEY CONTRIBUTORS: ANQI ZHANG, JAMES SEVIK, MICHAEL PAMMINGER

Argonne National Laboratory

Project ID: ACE084

DOE Sponsors: Gurpreet Singh, Leo Breton

June 8, 2016

OVERVIEW

Timeline

- Project start: FY 2013
- Project end: FY 2016
- Transitioning to VTO Lab Call 2017

Budget

- Funding in FY13: \$400k
- Funding in FY14: \$350k
- Funding in FY15: \$500k
- Funding in FY16: \$490k

Partners

- Ford Motor Company
- Sandia National Laboratories
- Oak Ridge National Laboratory
- Convergent Science, Inc.

Barriers

Robust lean-burn and EGR-diluted combustion technology and controls, especially relevant to the growing trend of boosting and down-sizing engines...

- Limited lean and EGR-diluted operating range
- Lack of systematic assessment of ignition systems and their potential in combination with lean/dilute combustion
- Absence of robust modeling tools
 - Dilute combustion
 - Cyclic variability
 - Spark-based ignition systems
 - Alternative ignition systems

RELEVANCE

- Market analysts forecast that gasoline fueled engines will continue to be the most-used option in the passenger car market in the United States for several decades, and as a result, will account for the largest fraction of fuel consumption [1].
- Recent SI light-duty thermal efficiency enhancements [2,3] delivered brake thermal efficiency values of 40-45% by:
 - Optimized intake flow, valve phasing, high %EGR, CR, S/B ratio, etc.
 - High spark-ignition energy → Impact on power requirements and durability
- EGR dilution is preferred over lean-burn due to after-treatment issues and is already suitable for the US market. Efficiency gain is somewhat limited. Lean-burn has the potential for higher efficiency increase.
- “Production style” and “high energy” igniters extensively tested. More insight needed into “unique non-conventional” systems (cold-plasma, lasers, etc.), which show promising performance [4].

1. US DRIVE Advanced Combustion and Emission Control (ACEC) Technical Roadmap for Light-Duty Powertrains, 2013.
2. Takahashi, D., Nakata, K., Yoshihara, Y., Ohta, Y. et al., SAE Technical Paper 2015-01-1254, 2015.
3. Ikeya, K., Takazawa, M., Yamada, T., Park, S. et al., SAE Int. J. Engines 8(4):1579-1586, 2015.
4. Briggs, T., Alger, T., and Mangold, B., SAE Int. J. Engines 7(4):1802-1807, 2014.

OBJECTIVES

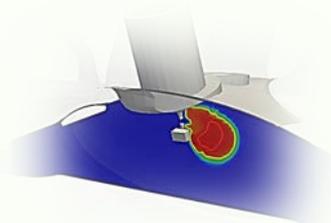
Maximize the thermal efficiency of automotive gasoline engines through improved EGR and lean dilution tolerance

- **Assess** advanced, non-spark based ignition systems systematically and determine compatibility with lean or EGR dilute combustion
- **Prioritize** research on advanced ignition systems based on feedback from US OEMs
- **Research** combustion stability issues with the goal to broaden the lean and EGR-dilute operating range
- **Develop** robust modeling tools to:
 - Analyze combustion stability and fundamentals of ignition
 - Evaluate the potential of igniters in a specific combustion system
 - Develop and screen new designs based on sound metrics

MILESTONES

Mo./Year	Description	Status
03/2014	Meet with Sandia to coordinate collaboration on ignition system projects	Completed
06/2014	Evaluate RANS for combustion stability predictions under dilute (lean/EGR) operating conditions	Completed
09/2014	Evaluate laser ignition performance and potential	Completed
12/2014	Benchmark RANS to LES for combustion stability assessments	Completed
03/2015	Characterize the interaction between in-cylinder flow and ignition source through laser multi-point ignition	Completed
06/2015	Stretch goal: Relative increase of 20% in indicated efficiency compared to GDI stoichiometric operation and production spark	On Track
09/2015	Validate ignition model against optical data	Completed
12/2015	Stretch goal: Plasma properties characterized for conventional as well as alternative ignition systems by using X-ray radiography	Completed
03/2016	Dilution tolerance further improved by using the transient plasma system with updated pulse generator and plug geometry	Completed
06/2016	Ignition model developed and validated against experimental data	On Track
09/2016	Dilution tolerance with laser improved with respect conventional spark systems by optimizing the location of the ignition point(s)	On Track

APPROACH



- Analyze combustion stability
- Improve existing ignition models
- Develop advanced ignition models
- Propose optimized configurations



- Evaluate efficiency improvements
- Define ignition power requirements
- Use advanced diagnostics (CORE)



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- Optical diagnostics (CORE)
- Data for model development and validation

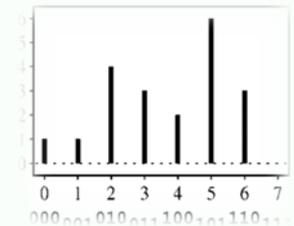


- Classify and rank ignition systems
- Identify progress in dilute combustion

Image credits: BorgWarner (left), ANL (center), TPS (right)

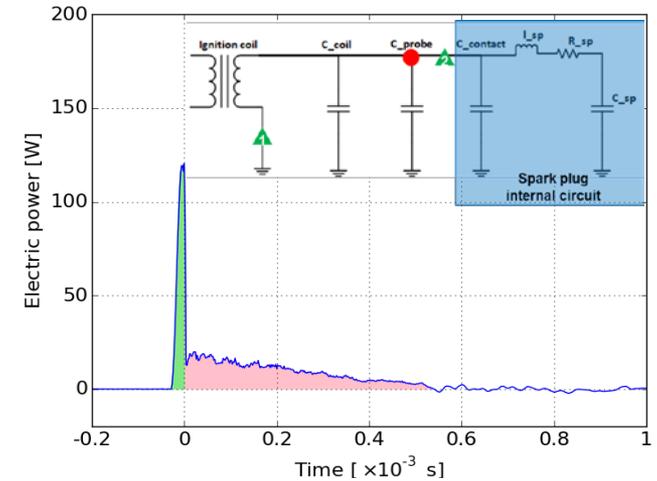
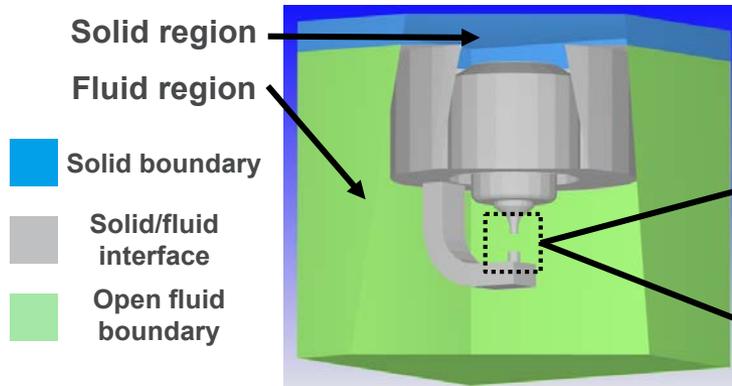


- Combustion and emissions diagnostics (CORE)



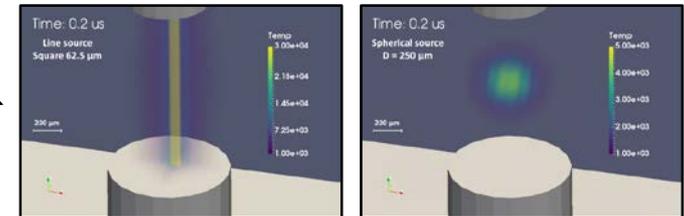
ACCOMPLISHMENTS FY16

Improved energy deposition model



Current models overlook many aspects:

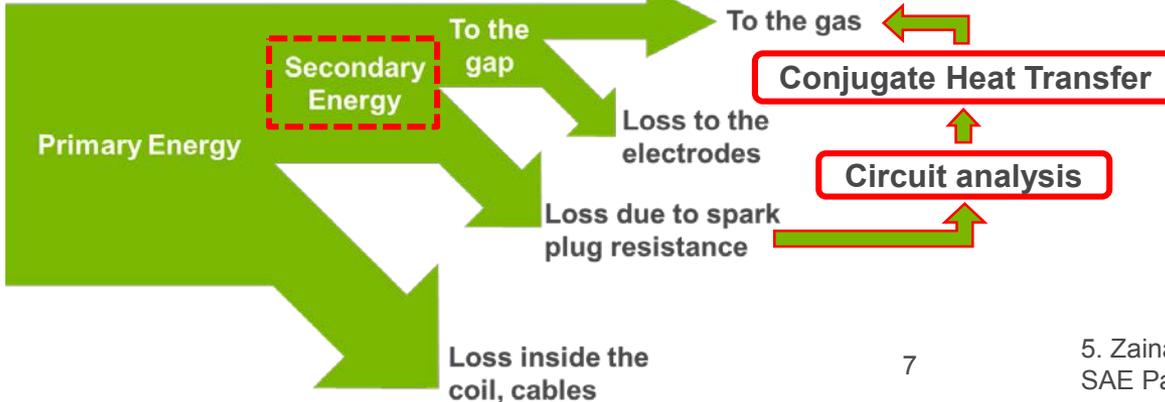
- Actual rate of energy (ROE) release
- Energy loss to the electrodes
- Shape of spark channel



Our approach takes all the losses into account:

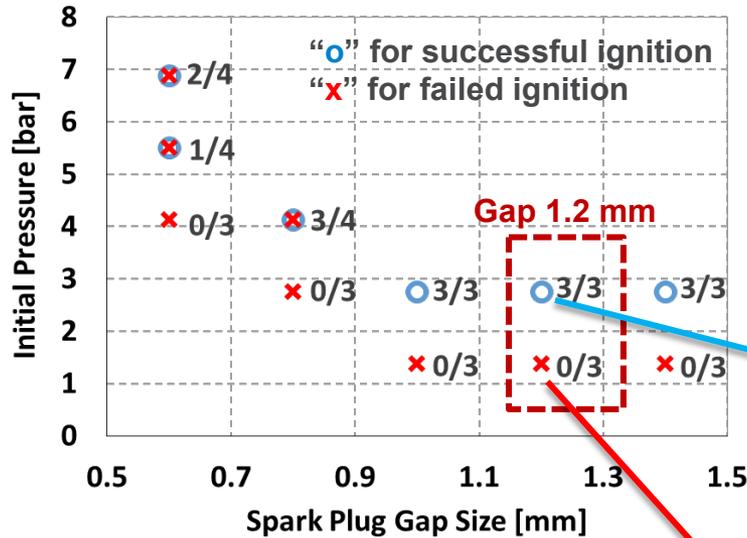
- No arbitrary ROE
- Actual energy in the gap
- Breakdown duration ($\sim\text{ns}$) is the remaining challenge

Spark discharge energy flow [5]



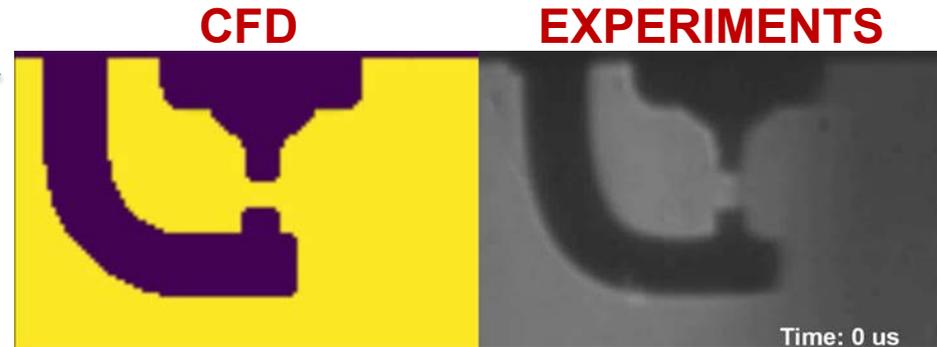
ACCOMPLISHMENTS FY16

Ignition model validated at quiescent conditions [6]



Experimental data from MTU

- Not the typical engine operating range
- Ignition behavior decoupled from the effect of the flow
- Excellent dataset to test model inputs

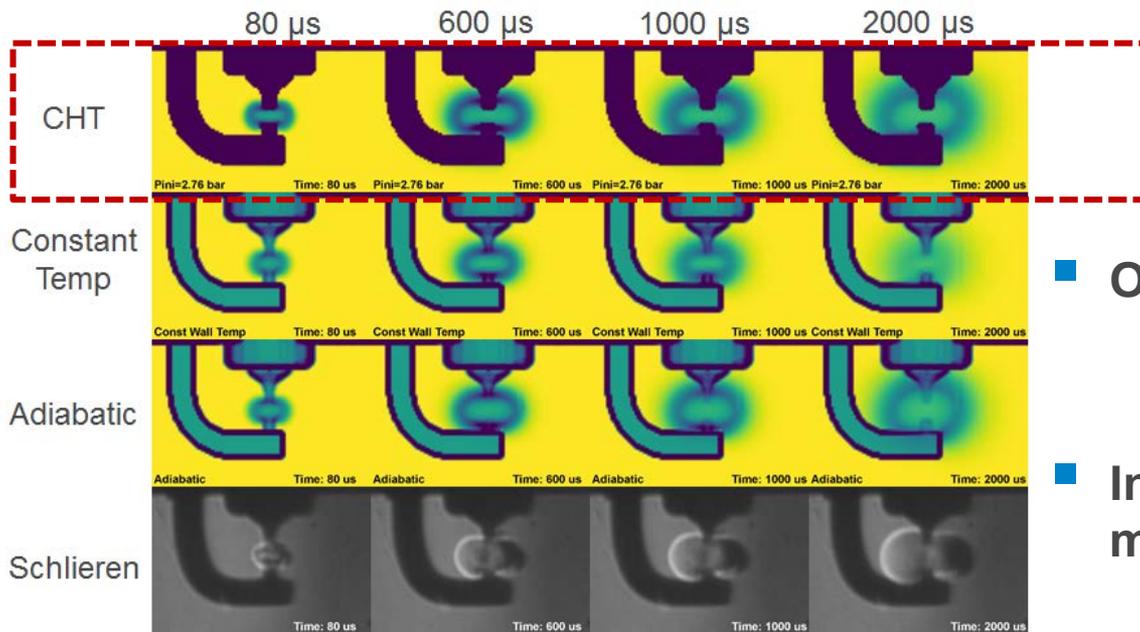
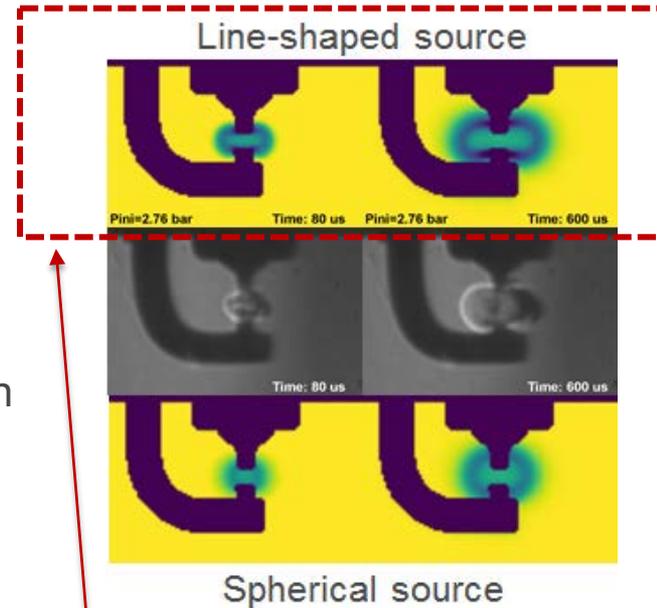


- Captured success/failure behavior
- Detailed ignition + detailed chemistry predicts kernel survival
- No criteria or sub-models needed
- Emphasizes the role of ignition BCs

ACCOMPLISHMENTS FY16

Effect of model BCs evaluated

- All the boundary conditions for the energy deposition model play a key role:
 - ROE might be known or unknown
 - Shape should be close to reality to deliver proper Temperature gradient and expansion/growth direction
 - Actual thermal loss should be considered using CHT calculations



This is what we use

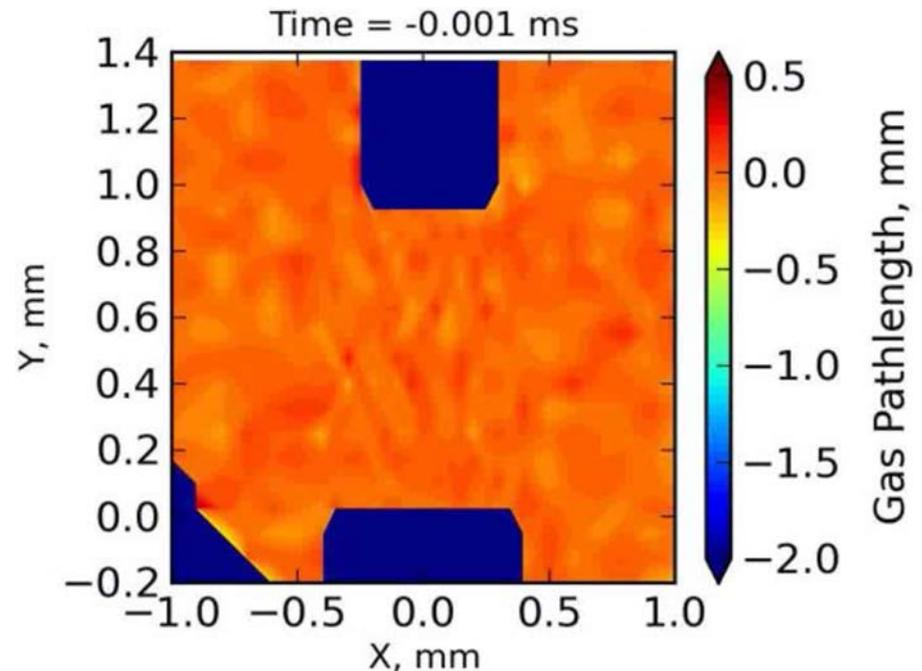
- Our improved model:
 - Relies on electrical properties
 - Predicts shape and trend
- Inaccuracies in setting the model deliver wrong behavior

ACCOMPLISHMENTS FY16

X-ray radiography used to characterize plasma properties

Spark in air, 3 bar pressure [7]

- Focused beam of X-ray at $5 \times 6 \mu\text{m}$
- Record 30-50 individual spark events at each measurement point, results are ensemble average
- Use Beer's Law to convert to a mass/area of gas in the beam compared to before the spark
- Convert to a pathlength of gas at the same ambient conditions for ease of interpretation



In general, what do we see?

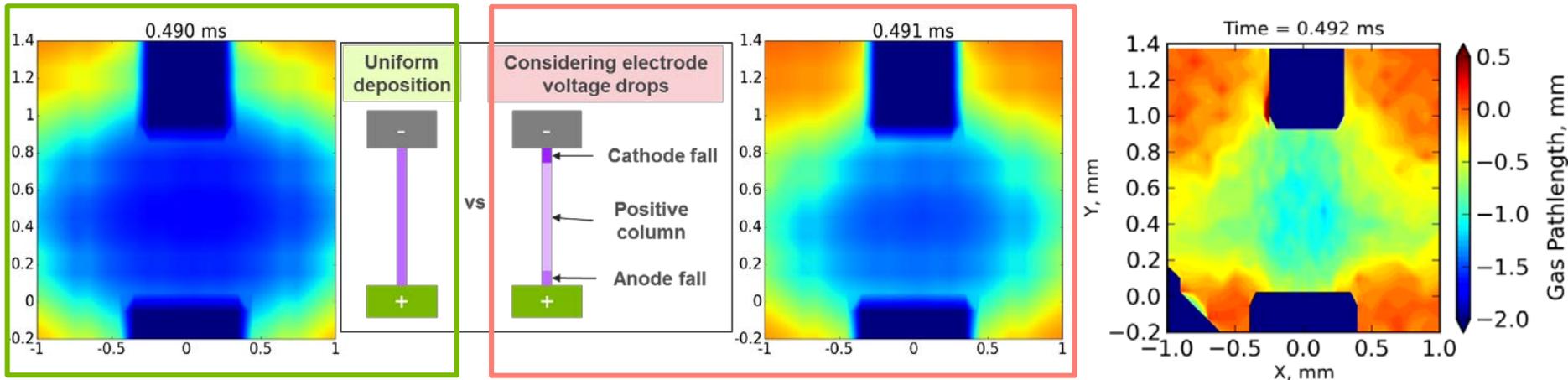
- “Negative” gas pathlength during the spark event. Gas has been heated, expands, and leaves a lower density than was present before the spark started
- Fundamentally, we are measuring density (well, a pathlength integral of density)

ACCOMPLISHMENTS FY16

X-ray radiography used for plasma modeling refinement

Simulate discharge in air at 3 bar ambient pressure:

- Same settings as in the vessel → Line shape (E = 28 mJ) + CHT
- CFD results post-processed in a fashion identical to X-ray measurements



Preliminary results are encouraging, considering inaccuracies

- Accurate discharge energy measurement is not available (E = 28 mJ is an assumption)
- Spark channel position varies from shot to shot with respect to the electrodes
- Discharge power varies spatially due to electrode voltage drop [8]
- Fuel chemistry only is used to account for disassociation of O_2 and N_2
- Main assumption of energy deposition model → 100% of discharge goes into thermal

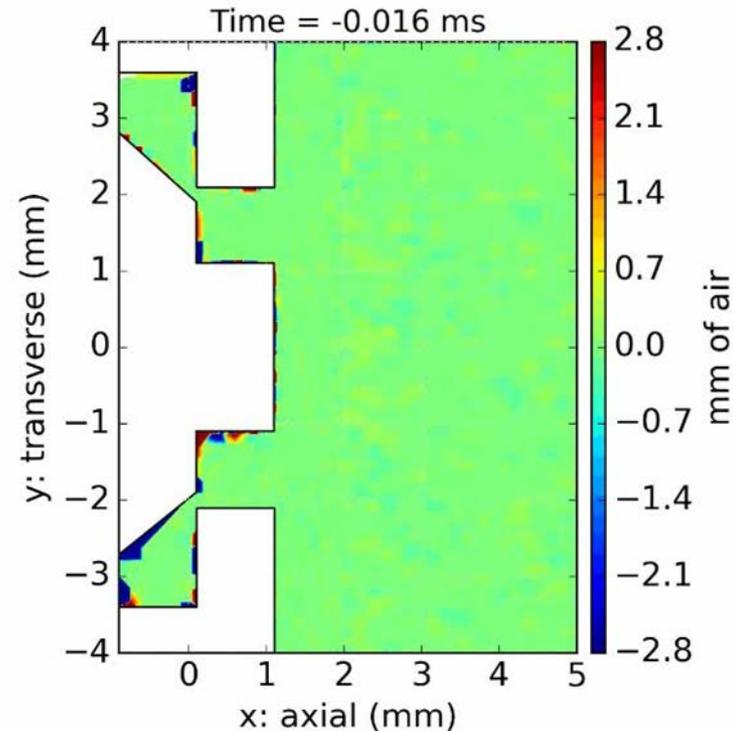
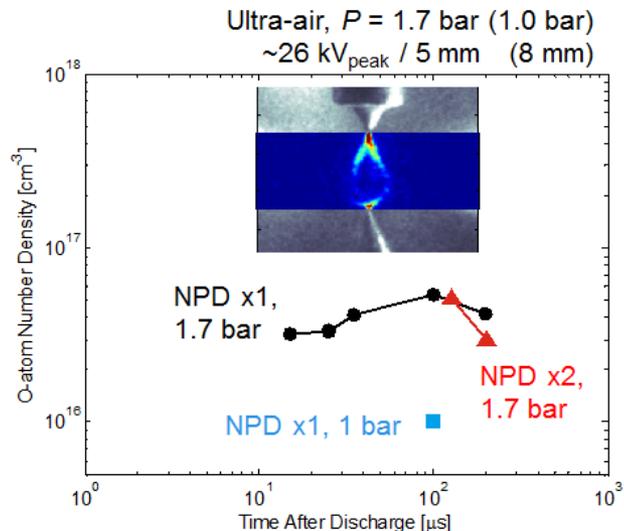
8. Maly, R. and Vogel, M., "Initiation and propagation of flame fronts in lean CH₄-air mixtures by the three modes of the ignition spark," Symposium (International) on Combustion 17(1):821–831, 1979.

ACCOMPLISHMENTS FY16

X-ray radiography applied to non-thermal plasma

Discharge in air, 3 bar pressure

- Removed electrodes to provide clear line of sight
- Nano-pulse delivery (NPD) from Transient Plasma Systems, Inc. (TPS)
- 20kV single pulse triggered at $t=0$
- Weaker signal with respect to conventional spark (expected)
- Single-pulse only tested, future diagnostics applied to multiple pulses



- Successful visualization of the discharge event
- Isaac Ekoto, SNL, is currently measuring O-atom concentration and energy efficiency through combined O-TALIF and calorimetry (ACE006)

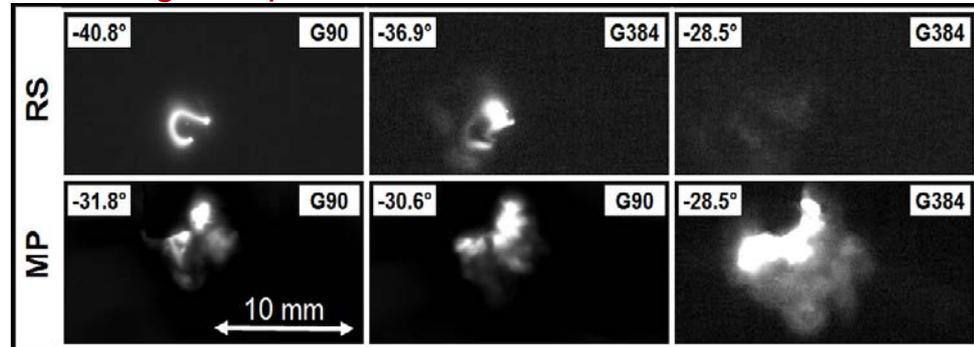
ACCOMPLISHMENTS FY16

Built computational model for ignition model validation at engine-like conditions

- Engine optical data of ignition and flame propagation is available for regular spark and multi-pulse transient plasma systems [9]
- To match experimental data, the cylinder flow has to be properly described by CFD simulations

9. Sjöberg, M., Zeng, W., Singleton, D., et al., SAE Int. J. Engines 7(4):1781-1801, 2014

RS = Regular spark



MP = Multi-pulse transient plasma

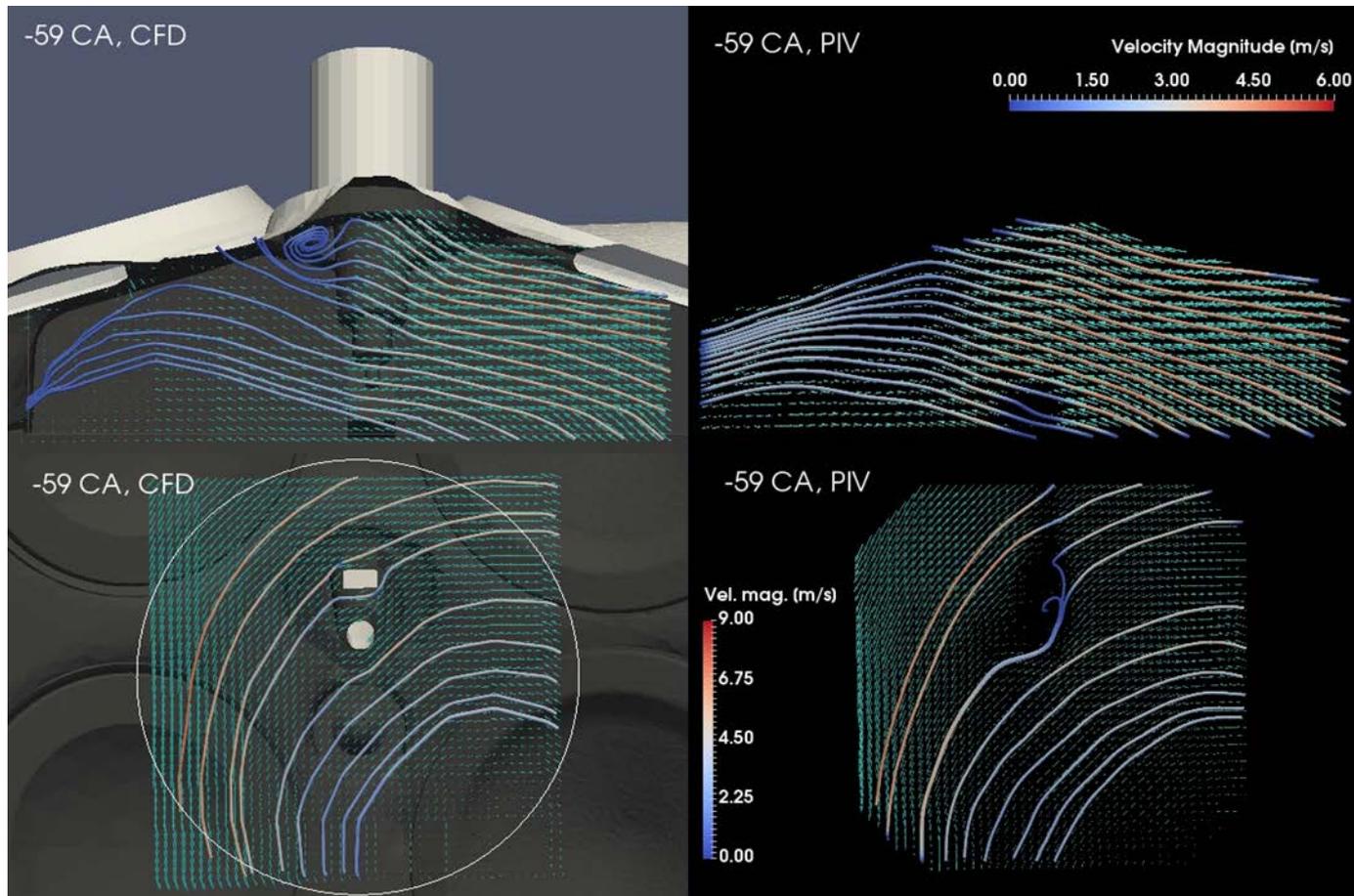


- The full computational domain of the DISI engine at Sandia National Laboratories has been recently built to evaluate ignition models for conventional and alternative ignition systems under turbulent flow conditions
- PIV measurements for validation have been shared by our project partners (Magnus Sjöberg and Wei Zeng, SNL)

ACCOMPLISHMENTS FY16

DISI SNL cylinder flow validated

PIV measurements from SNL
 Courtesy of Magnus Sjöberg and Wei Zeng

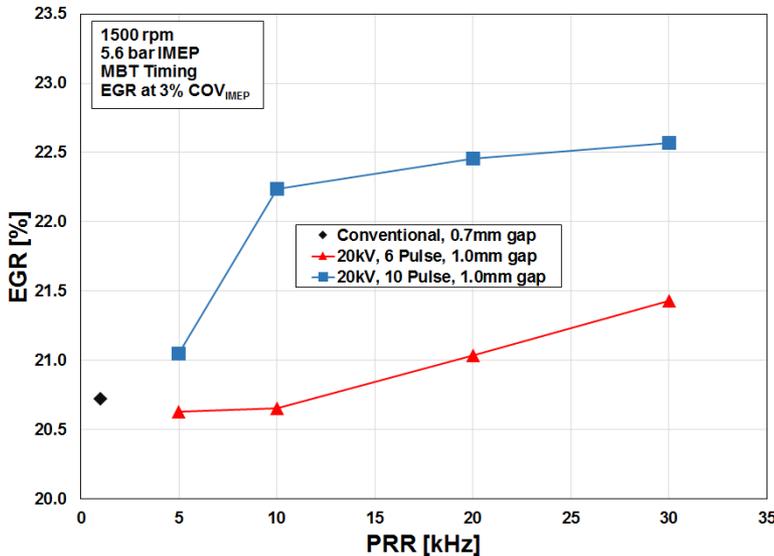
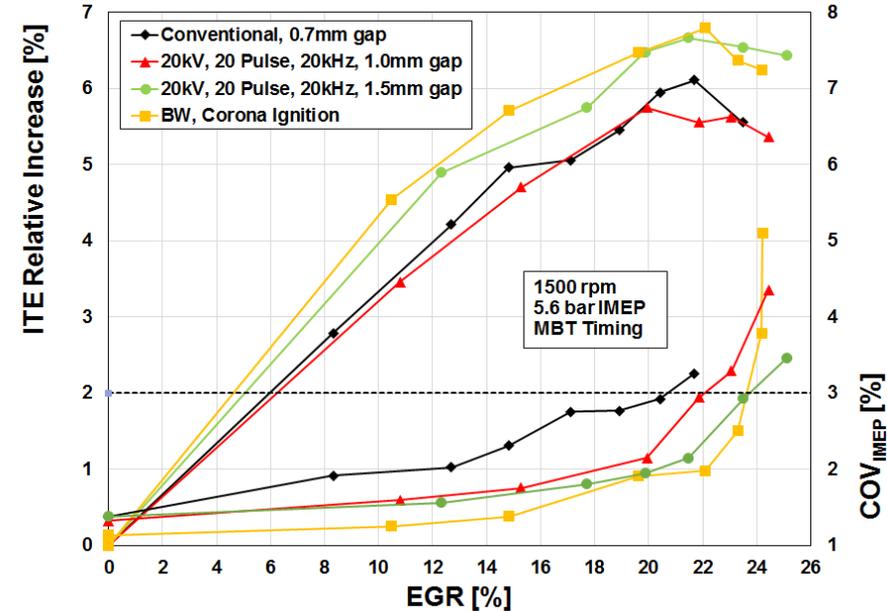


- Initial results show that most of the flow features can be captured
- Finer mesh should improve the flow calculations, in particular for tumble
- PIV measurements struggle to deliver velocity vectors near the spark-plug

ACCOMPLISHMENTS FY16

NPD transient plasma benchmarked to production and near-production baseline

- EGR and lean sweeps for:
 - Conventional spark
 - Transient Plasma System (NPD)
 - Borg Warner Corona Ignition
- Extended dilution tolerance for the TPS system respect to conventional spark
- TPS plug with larger gap matches BW Corona performance
- +7% maximum relative ITE for EGR dilution
 - Almost double values for lean dilution



- New TPS system reached PRR = 30 kHz
- High-voltage is expected to improve performance. Larger gaps could be successfully used
- Combination of high voltage, high PRR, and optimized plug design can further increase dilution tolerance and thermal efficiency

RESPONSE TO REVIEWER COMMENTS

- “...Laser ignition has been investigated for decades now, and many of the plasma/corona systems have been developed to near-production”...“ignition system testing should have an ongoing interaction with industry and also a continuing evaluation of existing published research so that it is clear how this project is going beyond studies that have already been done by others”
- ✓ This project aims at integrating with and possibly expanding previous/current work on advanced ignition systems, by using comprehensive approach (fundamental/applied research) and unique tools (advanced modeling and diagnostics).
- ✓ Our efforts are coordinated with DOE and USCAR, and prioritized based on literature.
- “...conventional coil ignition may not be the best baseline”...“comparison of any non-conventional ignition system with not only a traditional production-style system but with an inductive system, which is specifically intended for dilute operation”
- ✓ DOE focus is on non-inductive systems. We included near-production system results as baseline for future comparisons.
- “The reviewer would prefer to see the funding devoted more to the modeling development or to experiments which are unique from what has been published elsewhere”
- ✓ We have addressed this comment by steering the project direction more towards advanced diagnostics (X-ray) and advanced ignition model development.
- “The reviewer asked if there is a way to get the engine to operate at 35% EGR and closer to 45% BTE like Honda has demonstrated”
- ✓ Our approach is opposite with respect to most OEMs. Our goal is to evaluate, characterize, model, and improve advanced ignition systems in conventional GDI engines.

COLLABORATION AND COORDINATION



- Engine hardware support
- Project guidance with regular conference calls



- Coordination and update presentations
- Ranking and prioritization of ignition systems
- Development of evaluation guidelines



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- Optical diagnostics for model validation
- Data sharing and joint analysis of advanced igniters
- Coordination on ignition systems together with USCAR



Michigan Technological University®

- Optical diagnostics for model validation
- Joint publications

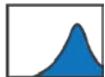


- Data sharing and joint analysis of perturbation result
- Joint publications



- Collaboration on modeling cycle-to-cycle variations (CCV)
- Joint publications
- Development/implementation of advanced ignition models

TPS
Transient Plasma Systems



- Testing advanced ignition systems
- Integration with existing SBIR and SBV programs

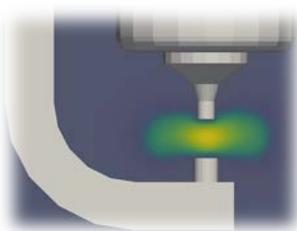
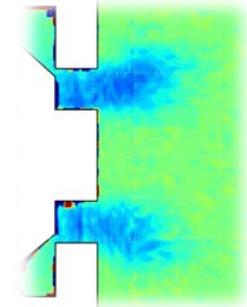
REMAINING CHALLENGES AND BARRIERS

- The limited lean and EGR dilute operating range achievable in "conventional" engine platforms somewhat understates the potential of advanced ignition systems in meeting the project ultimate goal, i.e. a significant increase of thermal efficiency with respect the baseline engine configuration
- The limited knowledge of ignition fundamentals, especially for non-conventional ignition systems, is a significant barrier for the development of those systems to meet the engine performance requirements and for the development of comprehensive models that can support the development and optimization of the ignition technology

PROPOSED FUTURE WORK

■ Advanced diagnostics for ignition systems

- X-ray (ANL) diagnostics for non-conventional ignition systems
- Coordination with calorimetry/O-TALIF measurements performed by Isaac Ekoto, SNL

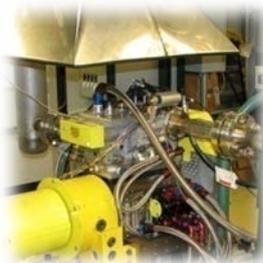


■ More physics in the computational model

- Both energy and species deposition
- Accounts for thermal and non-thermal plasmas
- Detailed plasma chemistry
- CCV using HPC (collaborative effort ANL/CSI/ARL)

■ Better characterization of ignition performance in engines

- In-cylinder imaging used to evaluate ignition systems
- Effect of the ignition source on flame development angle
- Ultimate source for model validation



■ Engine optimization to exploit advanced ignition systems

- Comprehensive knowledge of the discharge characteristics
- Detailed flow and thermal computational model of the igniter
- Select most promising solutions and run engine optimization

SUMMARY

Relevance

- Extend dilution tolerance to increase thermal efficiency of gasoline SI engines
- High-dilution tolerance demands high-performance ignition systems

Approach

- ANL combined experiments and modeling, applied and basic research
- Internal collaboration leveraging ANL core capability (X-ray diagnostics) to improve knowledge of ignition physics
- External collaboration with DOE Labs that have core capabilities in specific key fields

Technical accomplishments (1/2)

- Improved energy deposition model formulation
- Ignition model validated at quiescent conditions
- X-ray radiography used to characterize thermal plasmas properties and improve ignition model formulation

Technical accomplishments (2/2)

- X-ray radiography applied to non-thermal plasma
- Built computational model for ignition model validation at engine-like conditions and validated flow calculations
- NPD transient plasma benchmarked to production and near-production baseline

Remaining barriers

- Limited impact of advanced ignition systems on conventional engine technology
- Limited knowledge of non-conventional ignition physics

Future work

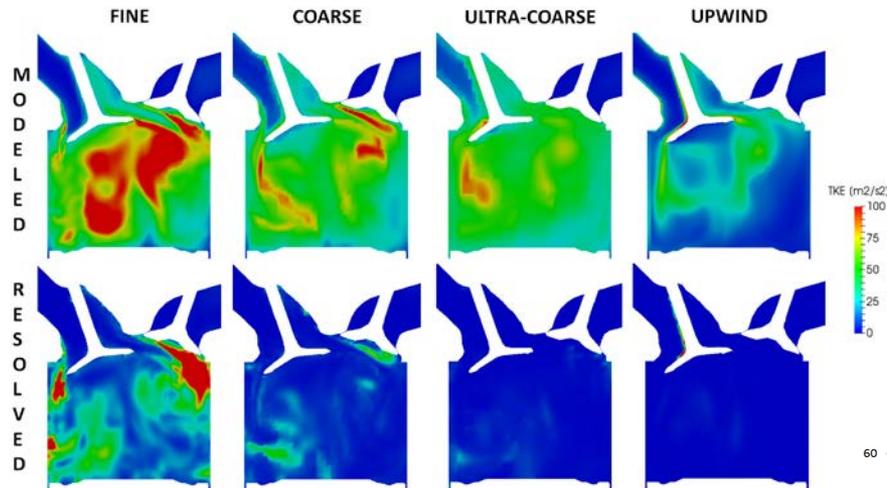
- Advanced diagnostics to accelerate physical understanding of the ignition process
- Comprehensive modeling to accelerate development of ignition systems
- Engine optimization to disclose full potential

**WE START WITH YES.
AND END WITH THANK YOU.
DO YOU HAVE ANY BIG QUESTIONS?**

BACKUP SLIDES

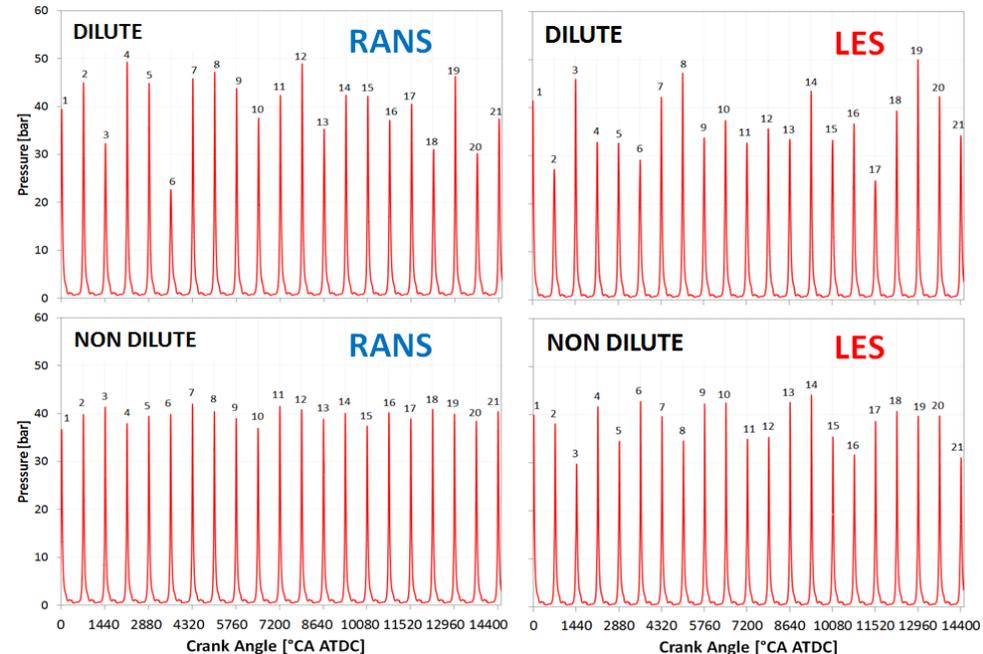
TECHNICAL BACK-UP SLIDES

Expanded understanding of RANS prediction of cyclic variability



- The stochastic and deterministic nature of CCV depends on the specific operating conditions [**]
- Dilute combustion shows increased deterministic features
- RANS and LES deliver similar CCV for dilute operation
- Stochastic behavior (LES) is needed to deliver better CCV predictions for non-dilute combustion

- Unsteady RANS (URANS) can resolve turbulence as much as it can model [*]
- In a SI engine, most of cycle-to-cycle variations (CCV) come from the flow:
 - Mixture formation, amount of residuals...
- Other variabilities can be taken into account in simulations → Experiments

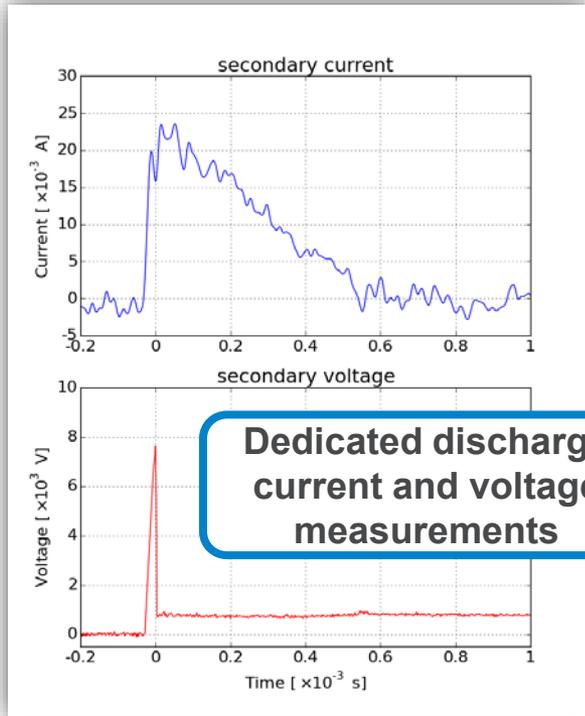


* Scarcelli R., et al., IMEM 2016 Meeting, 2016.

** Finney, C.E., Kaul, B.C., et al., IJER, Vol. 16(3) 366–378, 2015.

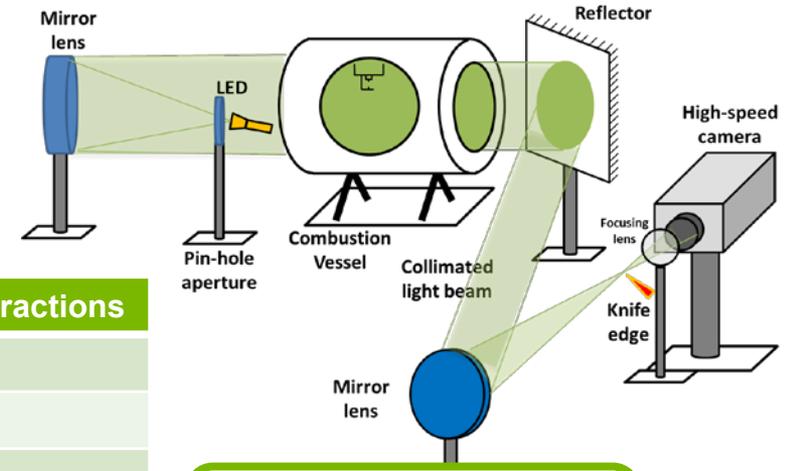
TECHNICAL BACK-UP SLIDES

Experimental Setup at MTU



Dedicated discharge current and voltage measurements

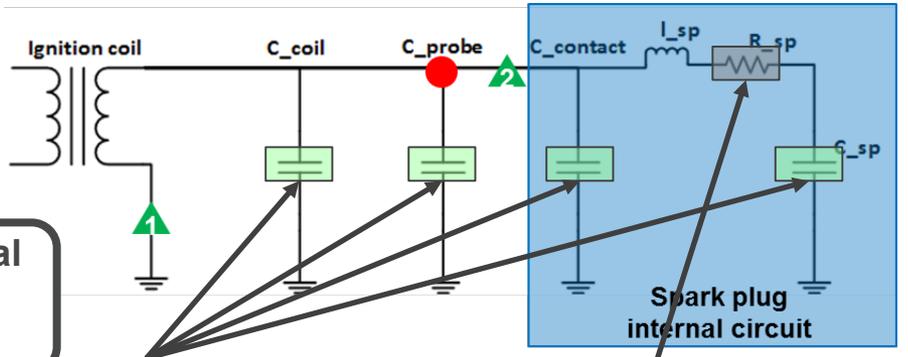
Species	Mole Fractions
CH4	5.5%
CO2	0.6%
N2	75.4%
O2	18.5%



High-speed schlieren imaging



Knowledge of electrical circuit and spark characteristics



Capacitors are charged during pre-breakdown

Losses from secondary circuit: resistance of spark plug and high-tension wires

TECHNICAL BACK-UP SLIDES

CFD Simulation Setup at ANL

Mesh Information

- Orthogonal Eulerian grids
- 1 mm base mesh
- 62.5 μm grid size near the spark gap

Physical Models and Parameters

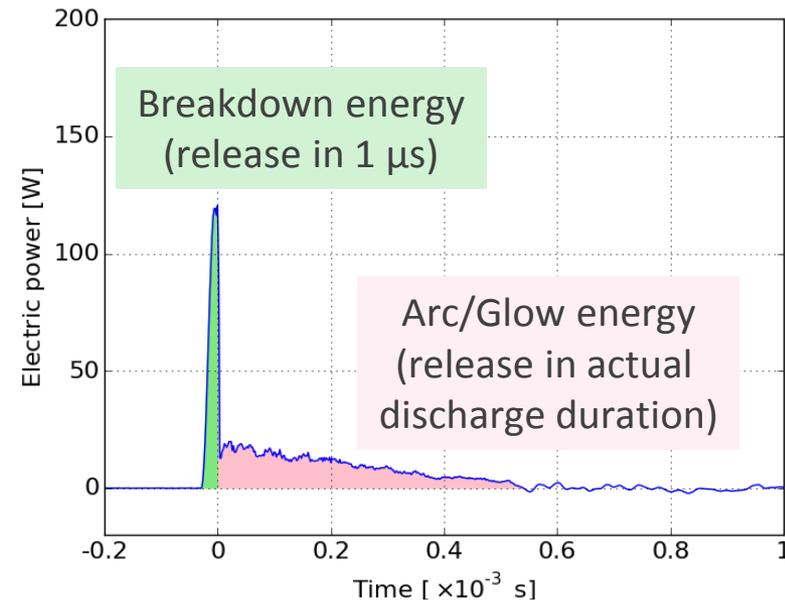
- RNG k- ϵ RANS Turbulence Model
- Detailed Chemistry Combustion
 - GRI-Mech 3.0

Conjugate Heat Transfer Simulation at solid/fluid interface

Energy Deposition Ignition Model

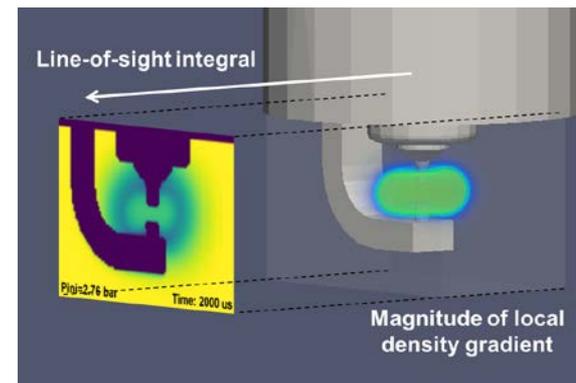
- 1 column of 62.5 μm cells across the spark gap
- Energy profiles differ by initial pressure

	E_bd	E_arc/glow	Duration
2.76 bar	1.90 mJ	4.20 mJ	550 μs
1.38 bar	1.70 mJ	4.46 mJ	680 μs



Pseudo-schlieren realization of numerical results:

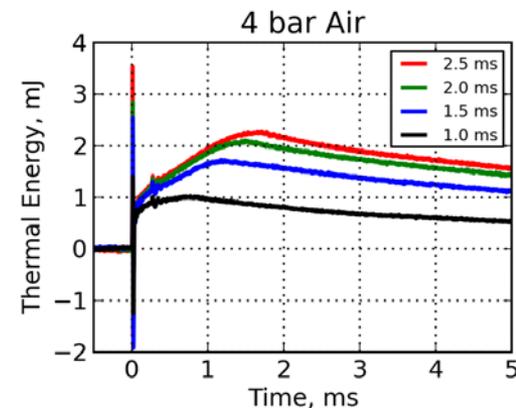
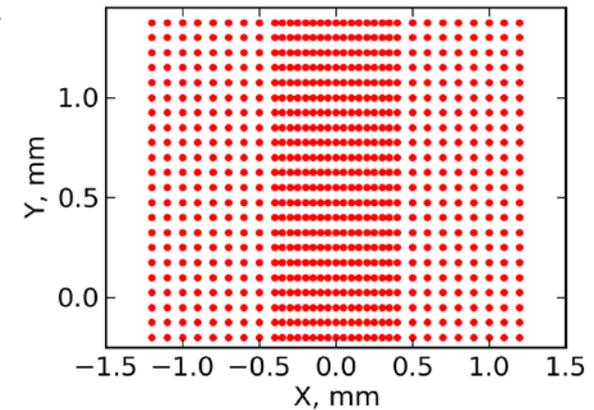
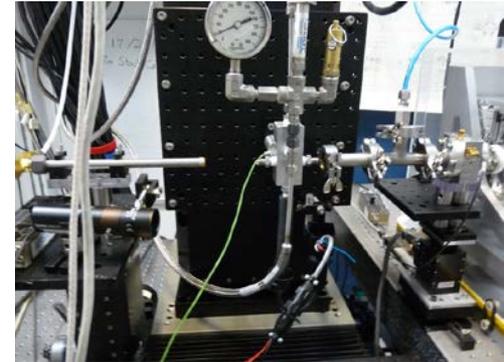
- Obtain the magnitude of local density gradient for each spatial location
- Integrate the magnitudes along the line of sight



TECHNICAL BACK-UP SLIDES

X-ray measurements at ANL

- Stock 75 mJ coil.
- Pressurized vessel to hold the spark plug
 - Experiments at room temperature
 - Around 0.4 L/min purge gas flow rate
 - Spark not in direct path of gas flow
 - Focused beam of X-ray at $5 \times 6 \mu\text{m}$ at 6 keV photon energy
 - Record 30-50 spark events at each measurement point
 - Sparks fire every 0.9 s
- Coordinates:
 - X transverse to the spark axis
 - Y along spark axis
 - Origin at center of ground electrode
- Displaced volume is proportional to the additional thermal energy present
 - Doesn't capture ionization energy
 - Doesn't capture dissociation energy
- Assume that ambient gas is ideal with constant specific heat
 - Not really if ionized or dissociated
 - Degree of ionization should be small



TECHNICAL BACK-UP SLIDES

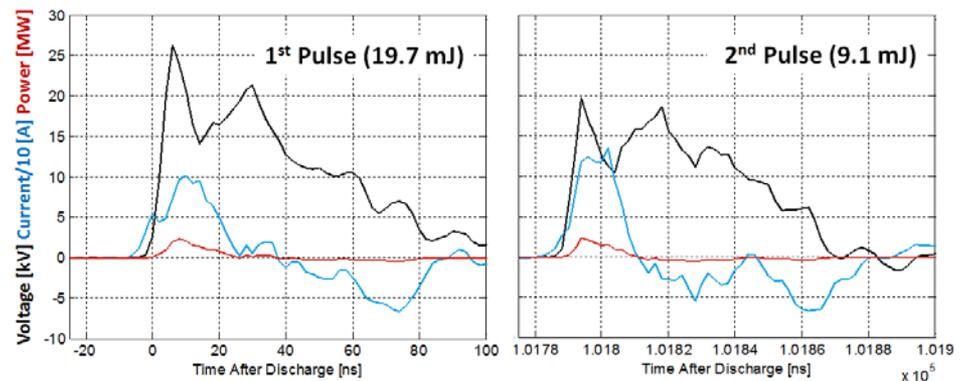
Endoscopic access used to visualize non thermal plasma

- Endoscopic access used to capture Transient Plasma Systems ignition event
- Successfully captured multiple spark events for combustion

Images at 2000RPM – 6bar IMEP – 6 pulses at PRR = 10kHz



- Variation in luminosity for each burst event visualized
- Is it a real behavior of the ignition event or an artificial effect due to the camera speed?
- Isaac Ekoto from SNL measured different energy delivered per pulse at the same PRR (ACE006)



Courtesy of Isaac Ekoto, SNL